High Temperature Superconductivity from Strong Correlation

Takashi Yanagisawa*

Electronics and Photonics Research Institute, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Abstract

It is important to understand the mechanism of high-temperature superconductivity. It is obvious that the interaction with large energy scale is responsible for high critical temperature $T_c$. The Coulomb interaction is one of candidates that bring about high-temperature superconductivity because its characteristic energy is of the order of eV. There have been many works for the Hubbard model including three-band d-p model with the on-site Coulomb repulsion to investigate a possibility of high-temperature superconductivity. It is, of course, not trivial whether the on-site Coulomb interaction leads to a pairing interaction between two electrons. We argue that high-temperature superconductivity is possible in the strongly correlated region by using the variational Monte Carlo method for the two-dimensional t-U-J-V model. The exchange interaction $J$ and the nearest-neighbour attractive interaction $V$ cooperate with $U$ and will act to enhance the critical temperature.

© 2015 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the ISS 2014 Program Committee.

Keywords: high-temperature superconductivity; strong correlation; Hubbard model; d-p model; t-U-J-V model; variational Monte Carlo method

1. Introduction

A basic question in the study of superconductivity is on an upper limit of the critical temperature $T_c$. It has been suggested that the maximum of $T_c$ is in the range from 30K to 40K when the superconducting transition is based on the electron-phonon interaction [1, 2]. The prime reason of low $T_c$ for the electron-phonon mechanism is that the Debye frequency $\omega_D$ is of the order of 100K and $T_c$ is reduced by more than one digit than $\omega_D$. In general, the electron-phonon coupling constant $\lambda$ is small. Thus there is an upper limit for $T_c$ within the electron-phonon mechanism. The interaction of large energy scale will be responsible for high temperature superconductivity. The electronic origin mechanisms of superconductivity are worth studying in the search of high temperature superconductors. The electronic interaction comes from the Coulomb interaction between electrons. From this point of view, it is important to consider the intra-atomic Coulomb interactions that are of the order of eV. Then a question arises as to whether the superconductivity is indeed induced by the Coulomb interaction. This subject has been studied intensively by using electronic models with the on-site Coulomb interaction $U$ including the two-dimensional (2D) Hubbard model [3-25], the d-p model [26-32] and also the ladder Hubbard model [33-37].
It remains matter of controversial as to whether the 2D Hubbard model accounts for high-temperature superconductivity. Most of the results of quantum Monte Carlo methods have failed to show the existence of superconductivity [12,13,17], and some results, however, still keep open the possibility of superconductivity [14, 23]. We must note that quantum Monte Carlo methods are methods being applicable only in the weakly correlated region where $U/t$ is not large and is at most from 4 to 5. The existence of superconductivity in strongly correlated regions should be considered further. This may account for properties of high-temperature cuprate superconductors.

2. Superconductivity in Strongly Correlated Region

Superconductivity in the strongly correlated region is described by using the 2D Hubbard model. The Hamiltonian is given by

$$H = \sum_{\langle ij \rangle} t_{ij} c^*_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}. \quad (1)$$

{$\{t_{ij}\}$ are transfer integrals and $U$ is the on-site Coulomb energy. The transfer integral $t_{ij}$ is non-zero $t_{ij} = -t$ for nearest-neighbor pair $\langle ij \rangle$ and $t_{ij} = -t'$ for next-nearest neighbor pair $\langle ij \rangle$; otherwise $t_{ij}$ vanishes. We denote the number of sites as $N$ and the number of electrons as $N_e$.

The ground state of the Hubbard model is divided into two regions, that is, a weak correlation region and a strong correlation region. When the Coulomb interaction $U$ is as large as or greater than the bandwidth $8t$, the ground state should be regarded as the strongly correlated one [38, 39]. We use the Gutzwiller ansatz and evaluate the superconducting condensation energy $E_{\text{cond}}$ for d-wave pairing. The wave function is

$$\psi = P_{N_e} P_{G} \psi_{\text{BCS}}, \quad (2)$$

where $P_G$ is the Gutzwiller operator $P_G = \prod_j \left( 1 - (1 - g)n_j \right)$ with the parameter $g$ in the range of $0 \lesssim g \lesssim 1$. The gap function $\Delta$ in the BCS function $\psi_{\text{BCS}}$ is regarded as a variational parameter. $P_{N_e}$ is a projection operator that extracts only the state with a fixed total electron number $N_e$. The condensation energy is defined as

$$E_{\text{cond}} = E(\Delta = 0) - E(\Delta = \Delta_{\text{opt}})$$

for the optimized gap function $\Delta_{\text{opt}}$.

We show $E_{\text{cond}}$ as a function of $U$ in Fig.1. $E_{\text{cond}}$ increases rapidly near $U \sim 8t$ as going into the strongly correlated region. $E_{\text{cond}}$ is very small in the weakly correlated region for $U < 8t$ and almost vanishes for $t' = 0$. For such small value of $E_{\text{cond}}$, it is certainly hard to obtain a signal of superconductivity by means of numerical methods such as the quantum Monte Carlo method. It follows from Fig.1 that high temperature superconductivity is possible only in the strongly correlated region. In particular, $U/t \sim 10-14$ is favorable for superconductivity. Similar results have been reported for $t'/t = -0.1, -0.25$ and $-0.4$ in Ref. [25].

![Fig. 1. The superconducting condensation energy per site as a function of $U$ in units of $t$ for $t' = 0$ and $t' = -0.2$ on $10 \times 10$ lattice. The number of electrons is $N_e = 88$ for $t' = 0$ and $N_e = 84$ for $t' = -0.2$.](image-url)
3. Enhancement of Superconductivity with Weak Attractive Interactions

Let us examine when the critical temperature $T_c$ is enhanced in correlated-electron systems. A layered crystal structure is obviously an important factor. The increase of the density of states in a layered crystal is certainly important and an interlayer interaction plays a significant role in finding new superconductors [40-44]. Apart from this, if there is an interaction that promotes superconductivity cooperating with the Coulomb interaction, $T_c$ will be increased. The d-wave pairing state in the Hubbard model will be more stabilized by weak nearest-neighbor attractive interactions.

We consider the exchange interaction $J$ and attractive interaction $V$ given as

$$H = \sum_{\sigma} \epsilon \sigma c_{\sigma}^\dagger c_{\sigma} + U \sum_{\langle g \rangle} n_{\uparrow g} n_{\downarrow g} + J \sum_{\langle g \rangle} \left( S_i \cdot S_j - \frac{1}{4} n_i n_j \right) + V \sum_{\langle g \rangle} n_i n_j. \tag{3}$$

This is so called the t-U-J-V model. In high-temperature cuprates, the exchange coupling $J$ arises as a super-exchange interaction between $d$ electrons in copper atoms, which is mediated by oxygen atoms. The last term with negative $V$ is expected to arise from the electron-phonon interaction [45]. In the variational Monte Carlo calculations, both $J$ and $V$ ($< 0$) act as an attractive interaction for nearest-neighbour pairs of electrons. The Gutzwiller ansatz is also adopted here. We use the electron-hole transformation to fix the electron number in $\psi_{\text{BCS}}$ instead of using $\psi_{\text{PN}}$ [46]. We show the results in Fig.2. In Fig.2 (a) we compare $-E_{\text{cond}}$ for $J/t = 0, 0.1$ and 0.2 where $U/t = 12$ and $t'/t = -0.2$. Basically the exchange coupling $J$ works effectively in a similar way to $U$ to form the $d$-wave pairing. We obtain a similar result for the interaction $V$, where the lowering of the energy $-E_{\text{cond}}$ by $V$ is smaller than that by $J$. It should be noted, however, that $J$ alone can not stabilize the $d$-wave pairing, which means that if $U$ is small, the $d$-wave superconducting state is not realized even for $J > 0$. This is shown in Fig.2 (b) where $-E_{\text{cond}}$ is shown as a function $\Delta$ with $J = 0.1$ and $t' = 0$ for $U/t = 8$ and $12$. $E_{\text{cond}}$ is very small for $U/t = 8$ and vanishes for small $U$. This indicates that the strong on-site correlation is needed so that the exchange coupling $J$ induces superconductivity.

![Graph](image)

Fig.2. The superconducting condensation energy per site as a function of $\Delta$ in units of $t$. (a) From the top, we set $J = 0, 0.1$ and 0.3 for parameters $U = 12$ and $t'/t = -0.2$. The number of electron is $N_e = 84$ on $10 \times 10$ lattice. (b) The condensation energy as a function of $\Delta$ in units of $t$ for $J = 0.1$ and $t' = 0$ where $U = 8$ and $U = 12$.

4. Summary

We have investigated the two-dimensional t-U-J-V Hubbard model. The condensation energy becomes large in the strongly correlated region, suggesting a possibility of high-temperature superconductivity. We mention here that there is a report that suggests a high-temperature superconductivity in the moderate-$U$ region by means of the dynamical mean field theory [24]. We must further clarify a consistency with the results obtained by the quantum Monte Carlo method.
The exchange interaction $J$ and the nearest-neighbor attractive interaction $V$ cooperate with the Coulomb interaction $U$ to enhance superconductivity. It is important that the exchange coupling $J$ alone cannot promote superconductivity if $U$ is small in the weakly correlated region. We expect that the strong $U$ and weak $J$ and $V$ may realize high critical temperature.

Acknowledgements

The author expresses his sincere thanks to K. Yamaji, M. Miyazaki, I. Hase and S. Koikegami for valuable discussions. A part of computations was performed at the facility of supercomputer center of the Institute for Solid State Physics, the University of Tokyo. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan.

References